Critical Dissolved Oxygen Minima in Splittail

Paciencia S. Young and Joseph J. Cech, Jr., University of California, Davis

Because the splittail population had declined dramatically and its original range has decreased by two-thirds (Herbold *et al* 1992; Moyle and Yoshiyama 1992; Meng and Moyle 1995) we conducted the study on "Environmental Tolerances and Requirements of the Sacramento Splittail, *Pogonichthys macrolepidotus* (Ayres)" to assist in effective water and habitat management and restoration of this species. This report on the critical dissolved oxygen minima (CDOMin) of splittail is part the study.

CDOMin were measured in young-of-the-year (1-4 g), juveniles (19-48 g), and subadults (72-187 g) using a modified method of Cox (1974) and Becker and Genoway (1979) defined by a loss of equilibrium (endpoint). As dissolved oxygen level decreased to the endpoint, splittail increased activity (turning, swimming, or darting around) then decreased activity but increased ventilatory frequency and gasping. Post-CDOMin recovery (restoration of equilibrium) generally took ≤ 3 minutes. Mean CDOMin values were low (9-18 torr oxygen partial pressure (PO_2) or 0.6-1.2 mgO_2/L) for all size groups of splittail (Figure 1).

The splittail's preferred habitat (slow-moving sections of rivers and sloughs) can have very low dissolved oxygen levels. For example, in Buckley Cove (in the Stockton Ship Channel part of the San Joaquin River), at midday at 92 cm below the surface, the dissolved oxygen level can drop to 0.4 mgO_2/L (DWR 1992). Fish generally avoid hypoxic conditions by moving away from them. However, when food abundance is low, fish (especially benthic foragers) readily forage in hypoxic waters (Rahel and Nutzman 1994). Splittail are benthic foragers (Caywood 1974; Daniels and Moyle 1983), and their short-term low dissolved oxygen tolerance may increase survival by permitting foraging in hypoxic benthic areas at times of low food availability.

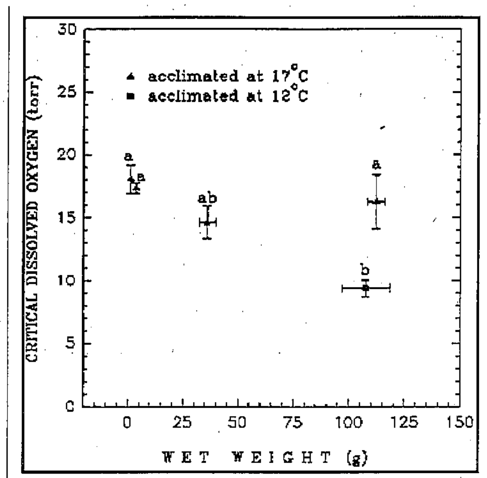

Figure 1
MEAN (± SEM) CRITICAL DISSOLVED OXYGEN MINIMA (TORR PO_2) OF DIFFERENT SIZE GROUPS OF SPLITTAIL
Subadults acclimated at 17 and 12 degrees Centigrade; Symbols with different letters are significantly different from each other; n = 4-10

Difference in size (1-187 g) had no significant effect on the CDOMin of splittail acclimated at 17°C. However, an increase in temperature increased the CDOMin. Subadult splittail acclimated at 17°C had a significantly higher ($P < 0.05$) mean CDOMin (16 torr PO_2 or 1.1 mgO_2/L) than those acclimated at 12°C (9 torr PO_2 or 0.6 mgO_2/L). This is probably because at higher temperature, fish have higher oxygen consumption rates than those at lower temperature (reviewed by Fry 1970) and, thus, require higher dissolved oxygen levels in the water. Davis (1975) explained that at higher temperatures, fish blood oxygen dissociation curves relating blood percentage saturation to the PO_2 typically shift to the right (indicating a higher oxygen requirement to fully saturate the blood), increasing the PO_2 threshold for hypoxia responses.

One must be cautioned in using the CDOMin for establishing criteria for dissolved oxygen levels. These values should be considered as extreme endpoints, approximating lethal limits. Complete loss of equilibrium in fish (endpoint) indicates the detrimental effects of the experimental variable so the fish becomes physically disorganized and loses its ability to escape from the harmful conditions, leading to its death (Becker and Genoway 1979). The International Joint Commission (1979) and the U.S. Environmental Protection Agency (1986) recommended that the effects of low dissolved oxygen level on growth be studied to determine minimum dissolved oxygen criteria. EPA (1986) reported that mortality or loss of equilibrium in salmonid and salmonid-like species occurred at the 1-3 mgO_2/L level. However, based on growth studies, the EPA established dissolved oxygen minimum levels of 9.5 mgO_2/L for early life stages, and 6.5 mgO_2/L in other life stages in salmonid and salmonid-like species, higher than the 1976 criterion of 5.0 mgO_2/L.

This study was supported by the Interagency Ecological Program for the San Francisco Bay and Sacramento-San Joaquin Delta. R. Brown facilitated this support. We thank S. Matern, L. Hess, S. Siegfried, G. Weis, J. Morinaka, L. Grimaldo, R. Baxter, H. Bailey, T. Hampson, and the Alosa and Longfin Groups headed by K. Heib and J. Arnold of DFG for assistance in splittail collection. We thank P. Lutes and B. Bentley of the UC-Davis Aquaculture and Fisheries Program for assistance in the fish maintenance system; L. Grimaldo for identifying and J. Wang for confirming identification of the small-size young-of-the-year; H. Zhou for statistical advice; and K. Jacobs and H. Proctor for the water quality monitoring data. We also thank D. Shigematsu, D. Irwin, M. Thibodeau, S. Cummings, C. Porter, J. Lorenzo, J. Heublein, J. Khoo, G. Cech, L. Brink, and P. Moberg for technical assistance.

Literature

Becker, C.D., and R.G. Genoway. 1979. Evaluation of critical thermal maxima for determining thermal tolerance of freshwater fish. *Environmental Biology of Fishes* 4:245-256.

Caywood, M.L. 1974. *Contributions to the Life History of the Splittail Pogonichthys macrolepidotus (Ayres).* M.S. Thesis, California State University, Sacramento.

Cox, D.K. 1974. Effects of three heating rates on the critical thermal maximum of bluegill. Pages 158-163 *in* J.W. Gibbons and R.R. Sharitz, editors. *Thermal Ecology.* AEC Symposium Series (CONF-730505), National Technical Information Service, Springfield, VA.

Daniels, R.A., and P.B. Moyle. 1983. Life history of splittail (Cyprinidae: *Pogonichthys macrolepidotus*) in the Sacramento-San Joaquin Estuary. *Fishery Bulletin* 81:647-654.

Davis, J.C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. *Journal of Fisheries Research Board of Canada* 32: 2295-2332.

Department of Water Resources. 1992. *Water Quality Monitoring Program Report, Decision 1485.* State of California, Sacramento.

Fry, F.E.J. 1970. Effect of environmental factors. Pages 1-98 *in* W.S. Hoar and D.J. Randall, editors. *Fish Physiology.* Vol VI. Academic Press Inc. New York.

Herbold, B., A.D. Jassby, and P. Moyle. 1992. *Status and Trends Report on Aquatic Resources in the San Francisco Estuary.* San Francisco Estuary Project.

International Joint Commission. 1979. *Report of the Review Committee for the Dissolved Oxygen Objective for the Great Lakes.* Great Lakes Science Advisory Board. Windsor, Ontario.

Meng, L., and P.B. Moyle. 1995. Status of splittail in the Sacramento-San Joaquin estuary. *Transactions of the American Fisheries Society* 124:538-549.

Moyle, P.B., and R.M. Yoshiyama. 1992. *Fishes, Aquatic Diversity Management Areas, and Endangered Species: A Plan to Protect California's Native Aquatic Biota.* The California Policy Seminar, University of California.

Rahel, F.J., and J.W. Nutzman. 1994. Foraging in a lethal environment: fish predation in hypoxic waters of a stratified lake. *Ecology* 75: 1246-1253.

U.S. Environmental Protection Agency. 1986. *Ambient Water Quality Criteria for Dissolved Oxygen.* Criteria and Standards Division. Washington, DC. EPA 440/5-86-003.

Temperature and Salinity Tolerances of Delta Smelt

Christina Swanson and Joseph J. Cech, Jr., University of California, Davis

In 1992, we began a study of the environmental tolerances and habitat requirements of the delta smelt, *Hypomesus transpacificus*, at that time a candidate species for listing under the State and Federal Endangered Species Acts. The objective of our research was to provide information useful for defining delta smelt critical habitat and developing management guidelines for the species. In this report we describe results of our studies on temperature and salinity tolerances of the delta smelt and implications of these results for management and protection of this fish.

Delta smelt spawn seasonally and complete their life cycle in a single year; life history stages tend to be strongly correlated with seasonal temperature regimes. Therefore, we conducted our experiments using juvenile (<4.5 cm standard length), subadult (4.5-6.0 cm SL), and adult fish (>6.0 cm SL) acclimated to seasonally appropriate ranges of temperatures that represented, for each life history stage, a low and high temperature level (juveniles and subadults in summer and fall, 17 and 21°C; subadults and adults in winter and spring, 12 and 17°C). Delta smelt may also exhibit seasonal preferences in salinity. Juveniles and subadults are most abundant in the brackish entrapment zone; adults move upstream to fresh water prior to spawning. Therefore, we measured temperature tolerances in fish acclimated to both fresh (0 ppt) and brackish (4 ppt) water.

Temperature Tolerance

Temperature tolerance limits were measured in terms of critical thermal maxima (CT_{max}) and minima (CT_{min}), a protocol in which the fish were subjected to relatively rapid change in temperature (6°C/h increase or 5°C/h decrease). The tolerance limit was defined by a sublethal response, loss of equilibrium, although in the wild such a response would probably be lethal.

Delta smelt tolerated moderate acute changes in temperature (Figure 1). CT_{max} was significantly affected by acclimation temperature; fish acclimated to warmer temperatures tolerated higher temperatures. However, the magnitude of the tolerated temperature increase was similar (5-7°C) for all three acclimation groups. An increase in salinity to 4 ppt significantly increased the delta smelt's tolerance to temperature increases. CT_{min} was less dependent on acclimation temperature and independent of salinity. Fish size (or life history stage) did not affect either CT_{max} or CT_{min}. These results show that delta smelt are

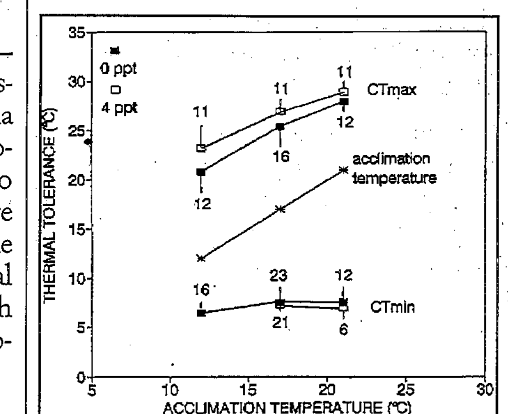

Figure 1
MEAN (±SD) CRITICAL THERMAL MAXIMA (CT_{max}) AND MINIMA (CT_{min}) OF DELTA SMELT ACCLIMATED TO 12, 17, and 21°C IN 0 AND 4 PPT
Sample sizes for each temperature/salinity combination are above or below the points.
CT_{min} in 12°C was only measured in 0 ppt.

eurythermal; they acclimated successfully to a relatively wide range of temperatures (12-21°C) and generally survived short-term exposure to acute temperature increases and decreases that are probably greater than the fish would normally encounter in the wild. However, in some areas within their range, delta smelt may be exposed to heated effluents and/or entrained in power plant cooling system water diversions where temperatures may reach 30°C (R. Pine, FWS, pers. comm.); our results strongly suggest that such exposure would be lethal to delta smelt. Furthermore, compared to a number of other delta fishes, delta smelt are more sensitive to acute temperature increases. Table 1 compares the CT_{max} of delta smelt to values measured for other fishes using the same methods and similar rates of temperature change. Splittail and inland silverside tolerated substantially greater increases in temperature. Even chinook salmon smolts acclimated to a slightly lower temperature had higher CT_{max}.

Table 1
COMPARISON OF CT_{max} OF
DELTA SMELT AND OTHER DELTA FISHES

Species	Acclimation Temperature (°C)	CT_{max} (°C)	Source
Delta smelt	12	21	Swanson & Cech (1995)
	17	25	
	21	28	
Inland silverside	17	31	Swanson & Cech (1995)
Chinook salmon	16.5	26-27	Swanson & Cech (1995)
Splittail			
Young-of-Year	17	31	Cech & Young (1995)
	20	32-33	
Juvenile	12	21	
	17	29	
Subadult	12	22	
	17	29	

Table 2
CHRONIC UPPER
SALINITY TOLERANCE LIMITS
OF DELTA SMELT
(Mean ± SD)

Temperature (°C)	Life History Stage SL (cm)	Upper Salinity Limit (ppt)
17	Juvenile 3.7 ± 0.3	18.7 ± 1.8 (n=15)
17	Subadult/Adult 5.9 ± 0.3	19.1 ± 2.1 (n=14)
21	Juvenile 3.7 ± 0.4	19.2 ± 1.9 (n=10)

Salinity Tolerance

Chronic salinity tolerance of delta smelt was measured for juveniles, subadults, and adults in 17°C and for juveniles in 21°C. In these experiments, individual fish were subjected to a gradual increase in salinity (2 ppt/12 h), and the tolerance limit was defined as the maximum salinity the fish survived for 12 hours. The slow increase in salinity allowed the fish to physiologically adapt to the changing osmoregulatory demands; therefore the tolerance limit represents the maximum osmoregulatory capacity of the fish for salinity increase.

Delta smelt tolerated chronic exposure to salinity from 0 ppt (fresh water) to 19 ppt (about 55% sea water) (Table 2). Neither acclimation temperature (17 and 21°C) nor fish size affected salinity tolerance.

The results show that delta smelt are euryhaline and that their osmoregulatory capacity is fully developed by 3 months post-hatch when the juveniles were tested. Furthermore, delta smelt are able to tolerate higher salinities than those in which they have been collected to date, suggesting that salinity is not the factor that limits their distribution to fresh and slightly brackish waters. The chronic salinity tolerances of delta smelt measured in these studies were similar to those measured for young-of-the-year and juvenile splittail (Cech and Young 1995).

Implications for Management

Moyle *et al* (1992) reported that delta smelt are apparently extremely sensitive to estuarine conditions, but the relationships between specific environmental conditions in the estuary and delta smelt abundance have not been well defined. The results of these and other ongoing studies in our laboratory can be used to define how temperature and salinity may limit delta smelt distribution and how, within the fish's range, these factors affect survival, physiology, and behavior. As an example, results of the CT_{max} experiments show how anthropogenic temperature fluctuations may adversely and disproportionately impact delta smelt. This type of information contributes to definition and management of dellta smelt critical habitat and improved protection of this threatened fish.

Acknowledgments

This study was funded by the California Department of Water Resources (contracts B-59449 and B-58959). We thank R. Mager and S.I. Doroshov (Department of Animal Science, UC Davis) for their help developing techniques for collection of delta smelt. We also thank the California Department of Fish and Game, particularly D. Sweetnam, G. Aasen, J. Lott, and the Bay/Delta boat crew, for their invaluable cooperation and assistance collecting delta smelt. P. Young (Department of Wildlife, Fish, and Conservation Biology, UC Davis), a number of undergraduate student assistants, including D. Shigematsu, C. Porter, S. Cummings, D. Irwin, M. Thibodeau, and NSF Young Scholars, S. Tannen, S. Aren, and J. Khoo, helped with fish collection, fish care, and data collection.

Literature Cited

Cech, J.J. Jr, and P.S. Young. 1995. Environmental tolerances and requirements of the Sacramento splittail, *Pogonichthys macrolepidotus* (Ayres). Final Report, Interagency Ecological Program for the San Francisco Bay/Delta. 56 pp.

Moyle, P.B., B. Herbold, D.E. Stevens, and L.W. Miller. 1992. Life history and status of the delta smelt in the Sacramento-San Joaquin Estuary, California. *Trans. Am. Fish. Soc.* 121:67-77.

Swanson, C., and J.J. Cech, Jr. 1995. Environmental tolerances and requirements of the delta smelt, *Hypomesus transpacificus*. Final Report, California Department of Water Resources. 77 pp.

Suisun Marsh Diversion Screening Program

Frank Wernette, Department of Fish and Game

Suisun Marsh entrainment studies in 1981 and 1982 identified 34 fish species in Montezuma Slough that were vulnerable to entrainment into unscreened diversions serving managed wetlands in the marsh. Species included chinook salmon, striped bass, and delta smelt. Based on those data, the Fish and Wildlife Service and Marine Fisheries Service incorporated related conditions in a Corps of Engineers regional maintenance permit for Suisun Resource Conservation District and the Department of Fish and Game. The primary goal was to reduce entrainment of winter-run chinook salmon and delta smelt. The Suisun Marsh Diversion Screening Program was begun to help fulfill those permit conditions, which were developed through formal consultation under Section 7 of the Federal Endangered Species Act with the Marine Fisheries Service and Fish and Wildlife Service.

The screening program consists of an extensive diversion assessment element and a fish screen installation element. The assessment element consists of an evaluation to determine whether diversions can be eliminated, downsized, or consolidated; a fyke-net study of fish entrainment into 15 diversions (selected annually); and a mark/recapture evaluation using coded-wire-tagged chinook salmon.

Implementation of this screening program will also help address mitigation needs described in a DWR/DFG agreement to offset impacts associated with the State Water Project, and meet objectives outlined in the State Water Resources Control Board's May 1995 Water Quality Control Plan for the San Francisco/Sacramento-San Joaquin Estuary and the Central Valley Project Improvement Act to reduce impacts to anadromous and special-status fish by screening unscreened diversions. Program implementation will also facilitate addressing mitigation needs associated with the Tracy Fish Agreement and help guide screening funded through Category III.

The program, and the environmental documentation associated with it, will help expedite the permitting process so that screen installations funded from any of the above sources can proceed as rapidly as possible.

The SWRCB 1995 Water Quality Control Plan lists the reduction of losses of all life stages of fishes to unscreened water diversions as a high priority action. The proposed screening program is consistent with that level of emphasis. One goal of the Water Quality Control Plan is to increase transport of fish, such as delta smelt, into Suisun Bay. Screening diversions will help protect fish transported into this area. The screening program will work synergistically with the Water Quality Control Plan to begin the recovery of fish populations.

Significant efforts were already underway through the DWR/DFG agreement and the CVPIA to install screens to prevent entrainment of fish in the estuary, particularly chinook salmon. The screen recently installed on Fish and Game's Grizzly Slough intakes is an example of that effort.

In the long term, screening will assist in recovery of winter-run chinook salmon, delta smelt, and splittail populations, assist in reducing impacts to other salmonids, and may help avoid future listings. Screening will ensure the long-term maintenance of seasonal wetlands in Suisun Marsh and ensure that habitat is maintained for a diverse assemblage of wildlife, including listed species such as salt marsh harvest mouse. Consistent with the ecosystem approach, the long-term viability of these important wetlands (at no serious risk to fish) will ensure that habitat is available for waterfowl and the numerous other water-dependent species.

A key to the success of the program will be the interagency involvement in various phases of the program such as selection of diversions for sampling, development of sampling protocol, and selection of high-priority diversions for screening.

In October 1995, an interagency team, along with stakeholder representatives and their biological consultants, will inspect diversions in the Suisun Marsh to select those for future sampling and to recommend 5-10 diversions for immediate screening.

New Interagency Program Home Page

Karl Jacobs, Department of Water Resources

Looking for data? The Interagency Program Home Page is now on-line! The Interagency Program file server uses the World-Wide Web to provide bay/delta information to researchers. Besides providing field data, the file server uses the versatility of hypertext to provide:

- A bibliography of current and historical documents (digital copies of some will eventually be available);
- Lists of Interagency Program personnel;
- Background on the organization and how it is structured.

Major sections of the home page are still under construction. We are adding: more background information on bay/delta biology, data summaries and analysis results from the monitoring programs, and data needed to more fully understand the estuary.

Field data are organized by program element; metadata are also provided. The field data are in a comma-delimitered text format, and format files are included to provide data users with the structure of the text files. The first five fields of the data files are: (1) RKI number, (2) station ID, (3) date, (4) time, (5) depth. Maps showing sampled locations and general information are also included.

Although not all our data have been placed on the server, most should be available by the end of November. Current work on the data portion includes placing data on the server, helping staff format data, developing a Wide Area Information Server interface, and upgrading communications to the server. Work is also underway to develop telephone modem access to the server.

We want your comments. Pass your recommendations on to the Webmaster or your representative on the new Data Utilization work team. Select the "Webmaster" button (mdng@water.ca.gov) on the home page or call Murray Ng at 916/227-1309.

The home page is accessed on the Internet using World-Wide Web browsers such as Mosaic, Netscape, or Lynx. The address is http://wwwiep.water.ca.gov.